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Analysis of infiltration processes into fractured and swelling soils as triggering factors of landslides

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Abstract The influence of rainfall in triggering landslides is a widely discussed topic in scientific literature. The slope stability of fractured surface soils is often influenced by the soil suction. Rainfall, infiltrating into soil fractures, causes the decrease in soil suction and shear strength, which can trigger the collapse of surface soil horizons. Water flow through fractured soils can also be affected by soil swelling, and when the surface soil layers overlie a more permeable material, by capillary barrier effects.

These phenomena are rarely investigated using existing models, especially from the point of view of rainfall triggering surface landslides. For this purpose, we have developed a dual-porosity model that simulates water flow through fractured swelling soils overlying a more permeable soil. The model has been applied to a soil profile consisting of a thin layer of fractured loamy soil above a coarse sand layer, in order to investigate the influence of different rainfall intensities on the infiltration process, and on the distribution of the pore pressure that affects slope stability.

Keywords infiltration, rainfall threshold, shallow landslides

Introduction

Rainfall-induced landslides are an important topic in the scientific literature. There is mainly an interest in evaluating the rainfall threshold that triggers the slope failure (Frattini et al, 2009; Guzzetti et al., 2008; Picarelli et al., 2009; Pagano et al. 2010). The complexity of hydrologic and mechanic processes involved in rainfall-triggered landslides makes it difficult to develop a reliable hydrologic model that could be used to evaluate these thresholds, especially for stratigraphically complex situations.

There is empirical evidence that a long low-intensity rainfall can sometimes be more dangerous than a short and intense one (Cotecchia and Simeone, 1996), and that the singularity of an event is sometimes more relevant than its exceptionality. It is therefore important to analyse infiltration processes in detail, in order to better understand how rainfall events can affect the pore pressure in the soil and how they can trigger a landslide.

In particular, the stability of the surface unsaturated soil layer along a slope is often related to the soil suction in that soil layer. In unsaturated soils, rainfall infiltration induces significant changes in the pressure head distribution, causing a decrease in suction and shear strength, eventually triggering slope instability.

The presence of fractures in the topsoil accelerates infiltration and influences pore pressure variations, depending on rainfall intensity and soil properties (Beven and German, 1982; Jarvis et al., 1991). Additionally, soil swelling can cause a progressive closure of cracks and can also significantly influence water flow (Vogel, 2005). The mechanisms, triggering instability of surface fine-grained unsaturated soils overlying more permeable soils or rocks, could also be significantly affected by capillary barrier phenomena (Mancarella and Simeone, 2008). Combined effects of cracks, swelling materials, and capillary barriers can thus seriously influence the pressure head distribution and the slope stability of unsaturated soils.

Existing models either do not consider all these processes or have not yet been applied to evaluate slope stability and/or to predict rainfall thresholds. A reliable study of rainfall-induced landslides and infiltration by means of empirical or theoretical models should not exclude the analysis of relevant processes, which affect the soil behaviour under unsaturated conditions and the pressure head distribution. A study, evaluating infiltration mechanisms while considering all these conditioning factors, could be useful for better understanding the influence of rainfall in triggering landslides and for reliably defining hydrological risks.

During the last few decades various empirical hydrological models have been proposed (Caine, 1980; Brunetti et al., 2009; and others; see a recent review by Guzzetti et al., 2008) that relate precipitation and landslides using empirical relationships. These models do not always take into account many physical phenomena affecting soils (Picarelli and Vinale, 2007). Nor do they consider how hydrologic processes affect the location, timing, and rates of landslides, and how the land use and climate can influence slope stability (Iverson, 2000).

Recently, several theoretical models evaluating landslide phenomena (Tsai and Yang 2006; Pagani et al., 2010; and others) have been developed, based on topographic, geologic, and hydrologic variables, and on changes in land use. In addition, there is also a large number of models, such as the HYDRUS codes (Šimůnek et al., 2008), which simulate infiltration processes.

In this paper we propose a dual-porosity model (Šimůnek et al., 2003), in which fractures become progressively narrower during infiltration due to the water content increase in the swelling matrix. The presence of a coarse grained soil underlying the fine fractured layer, which creates a capillary barrier effect at the contact between the two types of soils (Galeandro and Simeone, 2010) is also considered.

The model is applied to a soil profile consisting of a fractured loamy soil overlying a coarse sand layer. Results show how the infiltration process and the water content distribution can be strongly affected by rainfall intensity, swelling phenomena, and the presence of the underlying capillary barrier, subsequently affecting the overall slope stability.

The model

The model simulates water flow in swelling fractured soils, which are considered to be dual-porosity systems. In the model. fractures represent the macroporous domain, and the soil matrix between them the microporous domain. The rainfall intensity is assumed to be constant. The soil is considered to consist of a homogeneous porous medium with vertical fractures (Fig. 1), which become progressively narrower during the infiltration process as a result of swelling of the matrix (Fig. 1a).

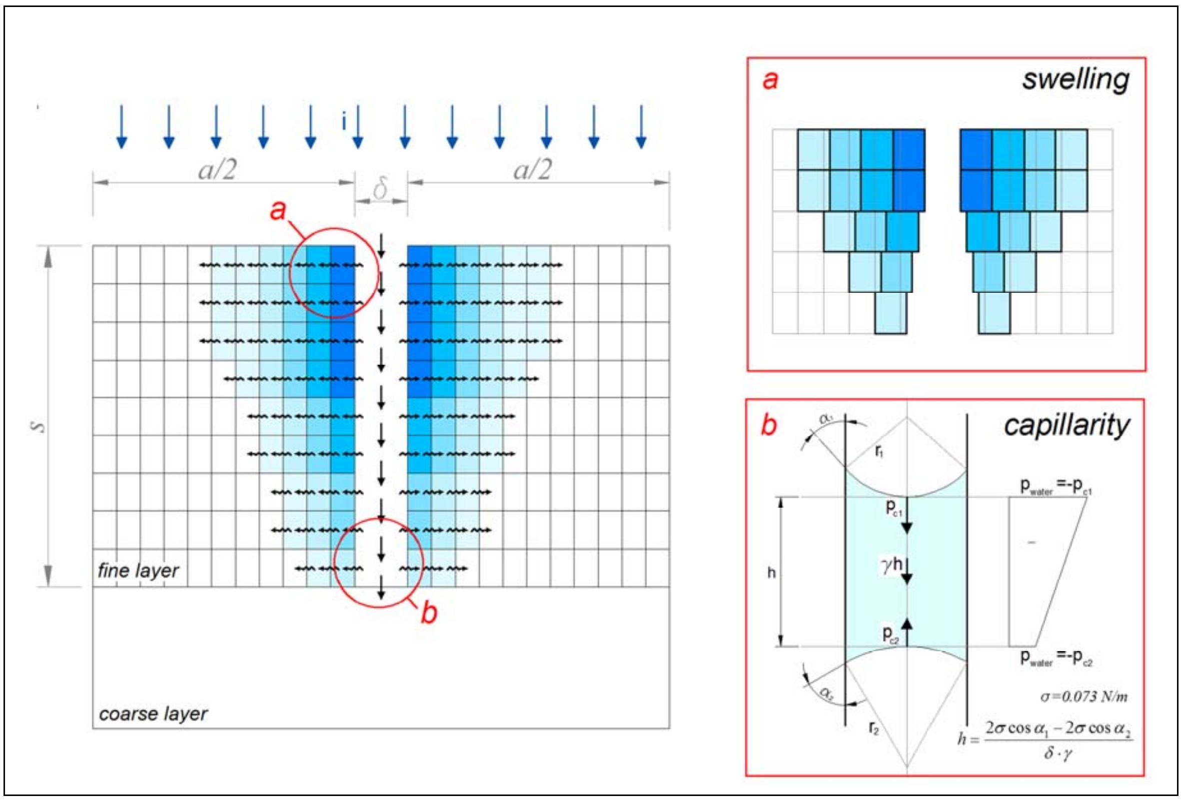

Figure 1 Schematic representation of a soil system and a flow model.

The model assumes that there is no vertical flow in the matrix and that all rainfall infiltrates into the fractures. Water flows into the cracks, from where it can horizontally infiltrate by diffusion into the matrix through the fracture-matrix interface (Fig. 1).

The unsaturated soil hydraulic properties are described using the van Genuchten (1980) and Mualem (1976) relationships. Water transfer through the fractures-matrix interface is modelled using the mass balance equation, which assumes that the matrix-fracture interactions are proportional to the pressure head gradient between the fractures and the matrix (Gerke and van Genuchten, 1993). Water flow in the matrix is described using the Richards equation for horizontal flow and the flow rate (cm^3/s) in the fractures is obtained as the difference between the fracture inflow rate and the amount of water laterally adsorbed by the matrix (Fig. 1).

Matrix swelling is evaluated assuming a linear relationship between the matrix volumetric water content and the soil volume (Novak, 2002), assuming that the maximum swelling at full saturation is 2% of the initial volume.

The coarse soil underlying the fractured fine-textured surface soil layer acts as a capillary barrier. Water accumulates in cracks and at the interface between the two soil layers up to a maximum capillary height (Fig.

1b). In the matrix, water is stored until the pressure head at the interface between the layers reaches a critical value, assumed to be the water-entry pressure head of the lower coarse layer (Shackelford et al., 1994; Stormont and Anderson, 1999).

The parameters needed to parameterize the model are:

- rainfall intensity i and its duration T;
- geometry of the fracture system (depth s, opening δ, and fracture spacing a);
- hydraulic properties and material status characteristics (saturated hydraulic conductivity of fractures K_{fs}; matrix initial water content θ_{init}, residual water content θ_{res}, saturated water content θ_{sat}, saturated hydraulic conductivity K_{ms}, and van Genuchten parameters α and n; maximum swelling percentage, and parameters relating swelling to water content).

In order to solve the flow equations, the system needs to be spatially discretized into elements of small dimensions in the x-z plane: the third dimension (in the direction of fractures) is assumed to be equal to 1 cm. The calculations are repeated at regular intervals.

Application of the model: results and observations

The case study

The model has been applied to a soil system involving the loamy fractured soil layer overlying a coarse sand. The fine-textured soil has been assumed to be 2 m thick, with a fracture interspacing of 0.5 m and a fracture opening of 0.01 m. Parameters describing the fracture network are summarized in Tab. 1. Soil hydraulic parameters of the soil matrix (the upper soil layer) are summarized in Tab. 2. The initial water content of the upper soil layer has been assumed to be 0.1 ($m^3\,m^{-3}$); i.e., close to the residual water content. A water-entry pressure head at the interface between the two layers has been assumed to be equal to 200 mm (Stormont and Morris, 1998).

Table 1 Parameters describing the fractures.

Fractures	
Saturated hydraulic conductivity K_{fs} (m/s)	1.00 x 10^{-3}
Spacing a (m)	0.50
Opening δ (m)	0.01
Thickness (m)	2

Table 2 Soil hydraulic parameters for the soil matrix (data from Leij et al., 1997).

Upper layer (loamy soil)	
Saturated hydraulic conductivity K_{ms} (m/s)	2.89 x 10^{-6}
Saturated water content θ_{sat} (m^3m^{-3})	0.43
Residual water content θ_{res} (m^3m^{-3})	0.078
α (van Genuchten, 1980) (m^{-1})	3.6
n (van Genuchten, 1980)	1.56
l (Mualem, 1976)	0.5

The model has been used to simulate 2 rainfall events with intensities of 2 and 20 mm/h (Tab. 3) and durations of 10 and 1 hour (denoted below as events A and B), respectively, i.e., with the same amount of rainfall per event of 20 mm. The time step equal to 10 seconds has been used.

Table 3 Parameters of two rainfall events and inflow rates into fractures.

Rainfall event	Rainfall intensity (mm/h)	Duration (h)	Inflow rate in fracture (cm^3/s)
A	2	10	0.0014
B	20	1	0.0139

Results and discussion

The behaviour of the system has been analysed in terms of water content and pressure head distributions, crack closure dynamics, and the capillary barrier breakthrough process during the two events (Figs. 2, 3 and 4). Results allow us to make several observations with regards to the evolution of water contents in the soil.

Water content and pressure head distribution dynamics

The presence of fractures in soils and the water flow through them produce water content and pressure head dynamics, along with corresponding shear strengths, in response to the rainfall intensity that is different than in homogeneous soils. Fractures significantly accelerate water flow and affect the dynamics of the water content distribution. The storage of water in the fractures and the matrix depends on the rainfall duration, crack opening, and functioning of the capillary barrier.

Initially, lateral adsorption of water into the soil matrix involves only a few centimetres of the soil near the matrix-fracture interface. Later, flow into the matrix depends on the flow in the fractures, on the rainfall intensity, and on the swelling process, which could close fractures and interrupt flow in both domains.

During low intensity rains (i.e., 2 mm/h, event A), water flows slowly into the fractures. Infiltrated water needs several hours to reach the maximum depth of the fractures, enabling the storage of water in the fractures and lateral inflow into the matrix. At the end of rainfall event A, there is significant absorption into the soil matrix involving the entire upper soil layer, where the soil suction becomes zero (Fig. 2).

For shorter and more intense precipitations (i.e., 20 mm/h, event B), water flows fast through fractures, reaching the bottom of the surface layer quite quickly (in about 20 minutes) and continuing to flow downwards. At the end of event B, horizontal water absorption involves only a thin portion of the upper soil (only about 5 cm) close to the fracture surface (Fig. 3).

Different water absorption into the matrix thus depends on rainfall intensity and on the interactions between water in the fractures and the matrix. Different rainfall intensities produce different water content distributions at the end of the rainfall events. Water is more uniformly distributed in the soil matrix for slow-intensity and longer events than for shorter and high-intensity precipitation. The average water content in the first 80 cm of the upper soil layer is close to saturation (0.428 $m^3\ m^{-3}$) for the low-intensity rainfall, while for the high-intensity precipitation the average water content is only about 0.136 $m^3\ m^{-3}$, with the maximum value of about 0.30 $m^3\ m^{-3}$.

Water content distributions, and corresponding pressure head distributions, are more critical for triggering surface landslide for low-intensity rains than for high-intensity precipitations.

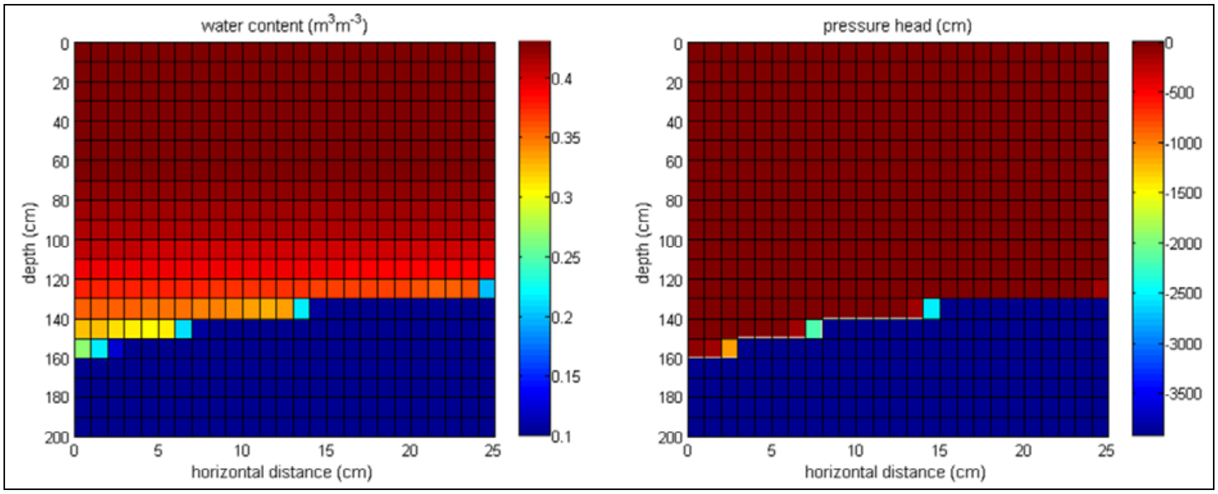

Figure 2 Water content and pressure head distributions at the end of the rainfall (Event A: 2 mm/h, 10 h).

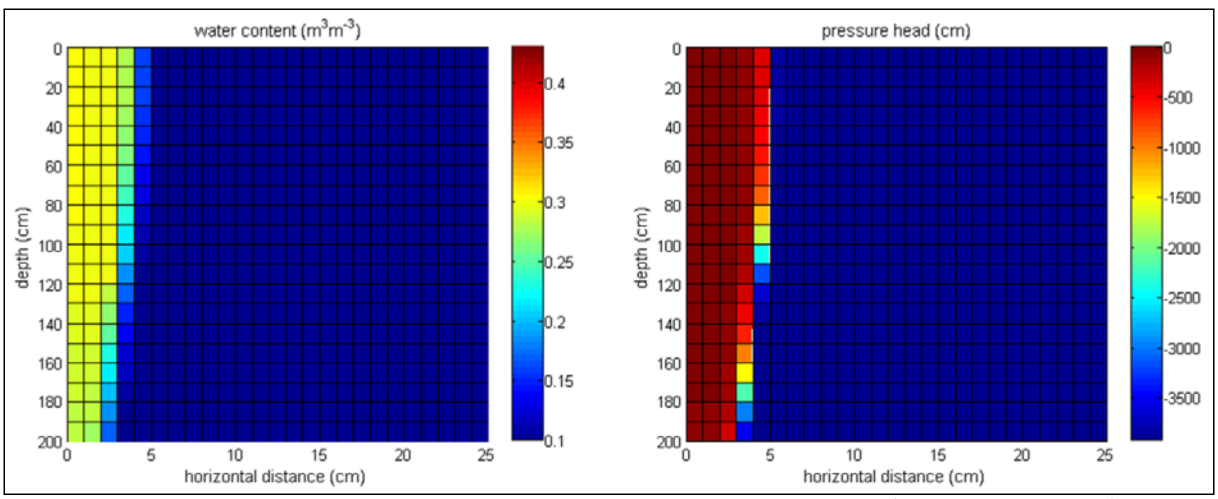

Figure 3: Water content and pressure head distributions at the end of the rainfall (Event B: 20 mm/h, 1 h).

Cracks closure dynamics

The process of crack closing starts at the soil surface and then propagates downwards toward the bottom of the surface soil layer. Results show how crack closing is controlled by the rainfall intensity and duration. Crack closing is quite irregular for low-intensity rains (event A, Fig. 4a). Horizontal water absorption is quite significant in the topsoil, inducing substantial swelling and causing the closure of surface cracks after several hours. Deeper parts of the loamy soil are not reached by infiltrating water and the cracks opening at the bottom of the surface soil layer remains equal to the initial value (1 cm). Closed cracks hold infiltrating water and prevent it from moving downward, producing pressure heads in the soil matrix near the surface, close to saturation (Fig. 2). For high-intensity precipitations (event B), the swelling process is quite uniform along the entire depth of the fractures. Also the closure of the fracture is almost uniform and much less significant (about 1 mm) (Fig. 4b).

Capillary barrier

There is no capillary barrier breakthrough for event A either in the matrix or the fracture because of the crack closures after about 7 h. Water cannot reach the coarse layer and break through the capillary barrier. The pressure head regime does not change at the interface between the two layers and the eventual stability failure could involve only the upper fine-textured layer.

The breakthrough of the capillary barrier below the fracture is quite a fast process in the case of event B when rain water can quickly flow down towards groundwater. The breakthrough occurs already after 2 minutes (corresponding to the rainfall of 0.61 mm). The breakthrough of the capillary barrier allows water to flow quickly through the fine layer towards the coarse one. While water flows quickly towards groundwater and can cause stability problems in deeper soil layers, it is less harmful for surface layers.

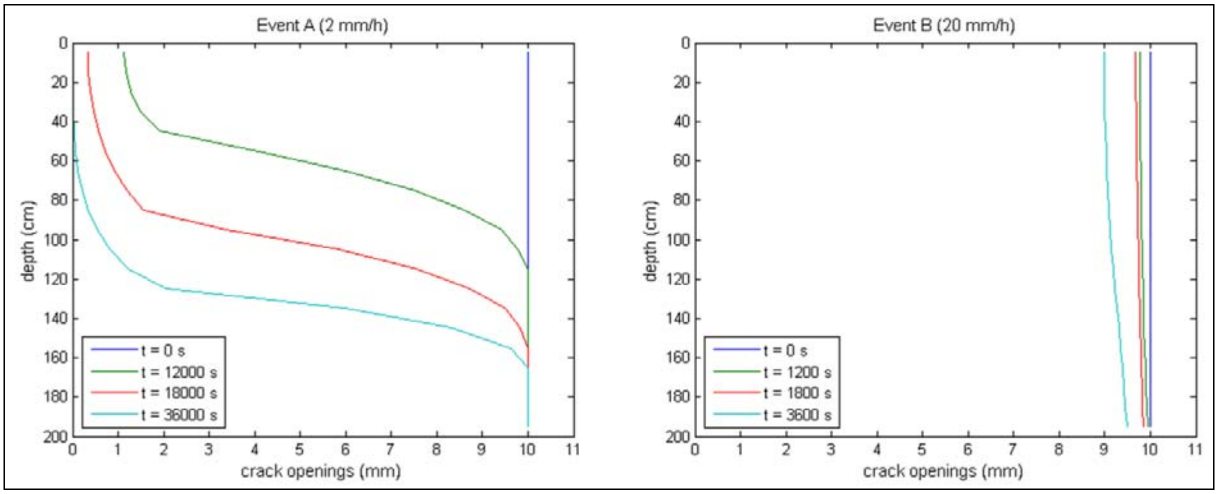

Figure 4 Crack closure dynamics

Conclusion

A new dual-porosity model is proposed, which simulates water infiltration into unsaturated fractured swelling soils, while considering matrix swelling and fracture closures, as well as the presence of a highly permeable soil underlying a less permeable one. The model enables us to better simulate the dynamics of the pore-water pressure in fractured swelling soils.

The model has been used to simulate infiltration into a loamy soil characterized by shrinking cracks for different rainfall intensities. Results show that water flow in the fractures and the matrix depends on rainfall intensities. For low-intensity precipitations, lateral water absorption is an important process, which may produce saturation of the entire soil matrix close to the soil surface. This results in significant variations in the pressure head distribution in the surface layer, which may be more critical for low-intensity rains than for high-intensity precipitations. Long-duration, low-intensity rain could thus potentially trigger surface landslides. Our calculations confirm that, sometimes, prolonged low-intensity rainfalls can be more critical than short high-intensity rainfalls in triggering soil landslides in the surface horizons. The application of the model showed that intense rainfall can cause capillary barrier breakthrough below the fractures in a very short time, since this depth can be reached quickly by infiltrating water.

The model helps us understand the influence of rainfall intensity, swelling, and capillary barrier effects on water content and pore pressure dynamics in surface layers and to evaluate the influence of rainfall dynamics. The ongoing research will involve the use of these types of models for evaluating rainfall thresholds in fractured swelling soils. The implementation of such infiltration model can contribute to the development of more reliable approaches to landslide risk analysis, showing how landslide susceptibility to rainfall can be influenced not only by the rainfall amount or intensity but also by the distribution of rainfall over time.

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